Optical instruments for Remote Sensing from Space

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ABSTRACT

This review covers the optical design of passive remote sensing optical instruments. The review concentrates on the design of spaceborne multispectral cameras and imaging spectrometers. The major designs that have been produced over the past ten years are discussed, and new designs for future imaging spectrometers are presented.

1. INTRODUCTION

The purpose of this review is to cover the optical designs that have been developed for passive remote sensing instruments over the last ten years. The review concentrates on the design of multispectral cameras and imaging spectrometers used on spacecraft, with some aircraft instruments included for completeness. A list of the instruments covered is given in Table 1, together with their acronyms and the references to the papers describing them. The earlier remote sensing instruments are well covered in Slater's book. [1]

Passive remote sensing instruments derive information from the scene by collecting the reflected solar radiation or emitted thermal radiation from each spatial area. This radiation is analyzed by the instrument for spectral content, and in some cases polarization properties.

Historically, remote sensing instruments have evolved from photographic film based systems. These were camera systems with filters, and scanner systems that wrote on film. The photographic film was then replaced with discrete electronic detectors, leading to whiskbroom scanning systems, such as Landsat, and the early infrared radiometers SMIRR and HCMR. Following on from discrete electronic detectors, silicon detector arrays were developed These led to pushbroom systems such as SPOT and MISR.

The development of infrared detector arrays has led to the whiskbroom imaging spectrometer systems, AIS, AVIRIS and MODIS-T, and pushbroom multispectral cameras such as SPOT4.

Currently, pushbroom designs are common for spectral areas where detector arrays are available, and whiskbroom designs are used for the infrared regions where only discrete detectors are available.

MULTISPECTRAL CAMERAS	
MISR[2]	Multi-angle imaging SpectroRadiometer
SPOT4[3]	HRVIR -High Resolution Visible and medium InfraRed Camera
SEVIRI[4]	Spinning Enhanced Visible-IR Imager
POLDER[5]	Polarization and Directionality of the Earth's Reflectances
VNIR/ASTER[6]	
SWIR/ASTER[7]	Advanced Spaceborne Thermal Emission and reflection Radiometer
TIR/ASTER[8]	
TM[1]	Thematic Mapper
MODIS-N[9]	Moderate Resolution Imaging Spectrometer - Nadir
IMAGING SPECTROMETERS	
MODIS-T[10]	Moderate Resolution Imaging Spectrometer - Tilt
MERIS[11]	Medium Resolution Imaging Spectrometer
SCIAMACHY[12]	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
ROSIS[13]	Reflective Optics System Imaging Spectrometer
AVIRIS[14]	Airborne Visible/Infrared Imaging Spectrometer
NIMS[15]	Near-Infrared Mapping Spectrometer
VIMS[16]	Visible and Infrared Mapping Spectrometer
SISEX[17]	Shuttle Imaging Spectrometer Experiment
HIRIS[18]	High Resolution Imaging Spectrometer
GENERAL	
MIPAS[19]	Michelson Interferometer for Passive Atmospheric Sounding
IMG[20]	Interferometric Monitor for Greenhouse Gases (ADEOS)
TES[21]	Tropospheric Emission Spectrometer
AOTF[22]	Acousto Optic Tunable Filter Spectrometer
MOES[23]	MultiOrder Etalon Sounder

Table 1. Remote Sensing Instruments

2. DESIGN OF OPTICAL REMOTE SENSING INSTRUMENTS

This section is concerned with the optical designs used for remote sensing instruments. A number of current instruments are compared, and the correlation between their functional performance and their optical design type is discussed.

The type of optical design chosen for a remote sensing instrument depends upon various requirements: the number of spatial and spectral bands, the spatial resolution and field of view, the spectral resolution and wavelength range, the entrance pupil diameter and f-number at the focal plane, The optical design is also strongly driven by the availability of detector arrays in the spectral region of interest.

The optical design selected for a system is that which can best meet the above requirements together with the constraints. Spaceborne remote sensing systems are constrained by mass, volume, power consumption and thermal environment. Nowadays, limited financial resources also provide another strong constraint.

2.1. Optical Performance

A comparison between the designs for optical remote sensing instruments is given in figure 1, in terms of the number of spatial and spectral bands for each system. The number of spatial bands given are those that arc intrinsic to the optical design, and does not take into account the usc of a scan mirror in the whiskbroom systems. The graph provides an interesting view of the three main types of remote sensing instruments: multispectral cameras, imaging spectrometers, and Fourier transform spectrometers.

The multispectral cameras, which have a small number of spectral bands, are contained in a column on the left. Thematic mapper, a whiskbroom scanner, with 16 spatial bands and 7 spectral bands provides an interesting comparison to the most recent designs. These pushbroom designs, SPOT4 and VNIR/ASTER, provide a high number of spatial bands by taking advantage of the latest detector arrays.

The imaging spectrometer designs lie diagonally on the graph, with the latest designs such as ROSIS and HIRIS providing a large number of spatial and spectral bands.

The pure pushbroom designs with one spatial IFOV lie along the bottom of the graph. This is the domain of the Fourier transform spectrometers, which have the largest number of spectral bands and the highest spectral resolution. The only imaging Fourier transform spectrometer shown is TES, with 16 spatial bands, that is being built for EOS.

The spatial performance of the remote sensing instruments is shown in figure 1. This graph maps out the IFOV (Instantaneous Field of View) and total FOV for each instrument, Again, the FOV is for the intrinsic design, and does not take into account the usc of the scan mirror in the whiskbroom systems.

For spaceborne remote sensing instruments the IFOV is driven by the requirement that enough photons be collected from the ground. Decreasing the 1 FOV directly reduces the solid angle of the light collected, which can only be compensated with a larger entrance pupil diameter. The IFOV of thematic mapper compares favorably with today's designs.

For imaging spectrometers the trend is for larger fields at lower spatial resolution, examples of this are MODIS-T and MERIS.

2.2, Multispectral Cameras

The basic components of a multispectral camera are shown in figure 3.11 consists of a telescope followed by a filter and a linear or area array detector. Most systems have a number of spectral bands, obtained through the usc of dichroic beamsplitters. In some designs the different field positions pass through different filters, and the spacecraft motion is used to superimpose the spectral bands for a given field point.

Figure 1. Spatial and Spectral Bands

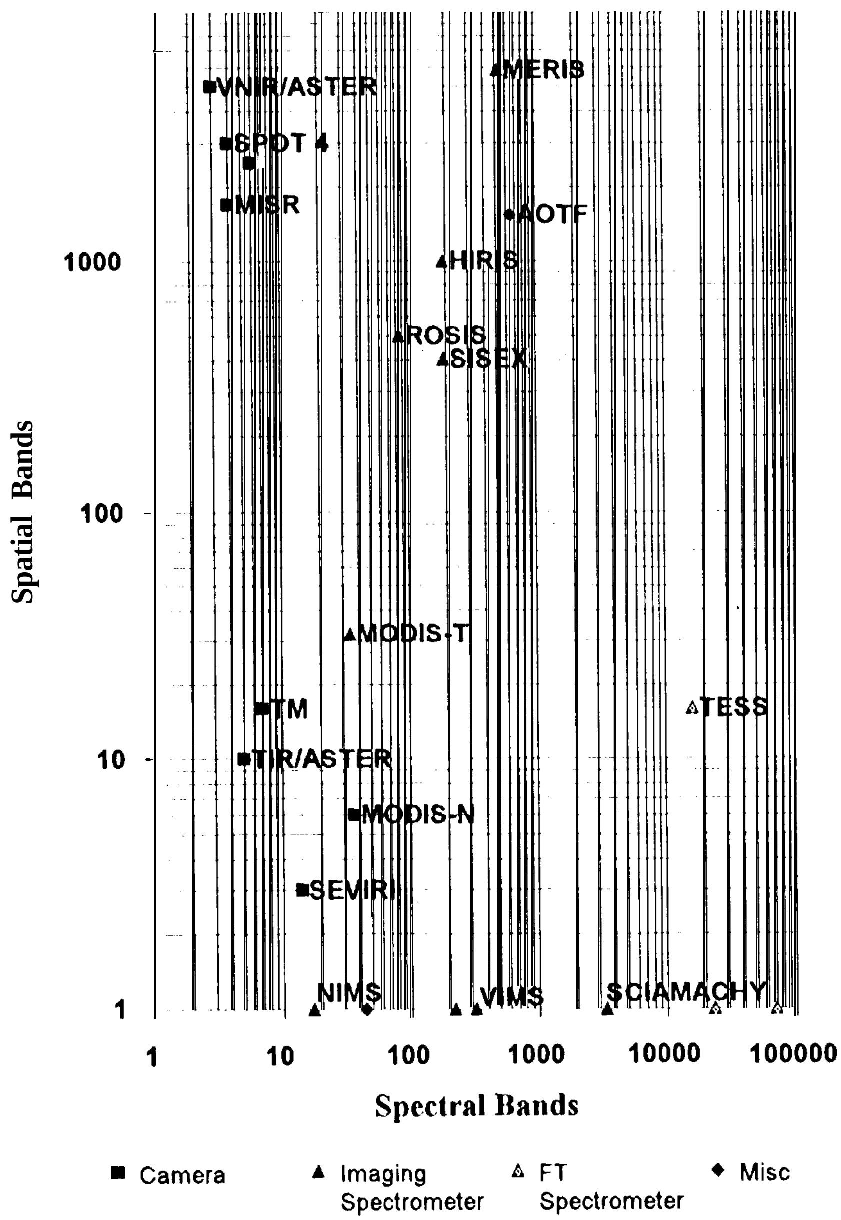
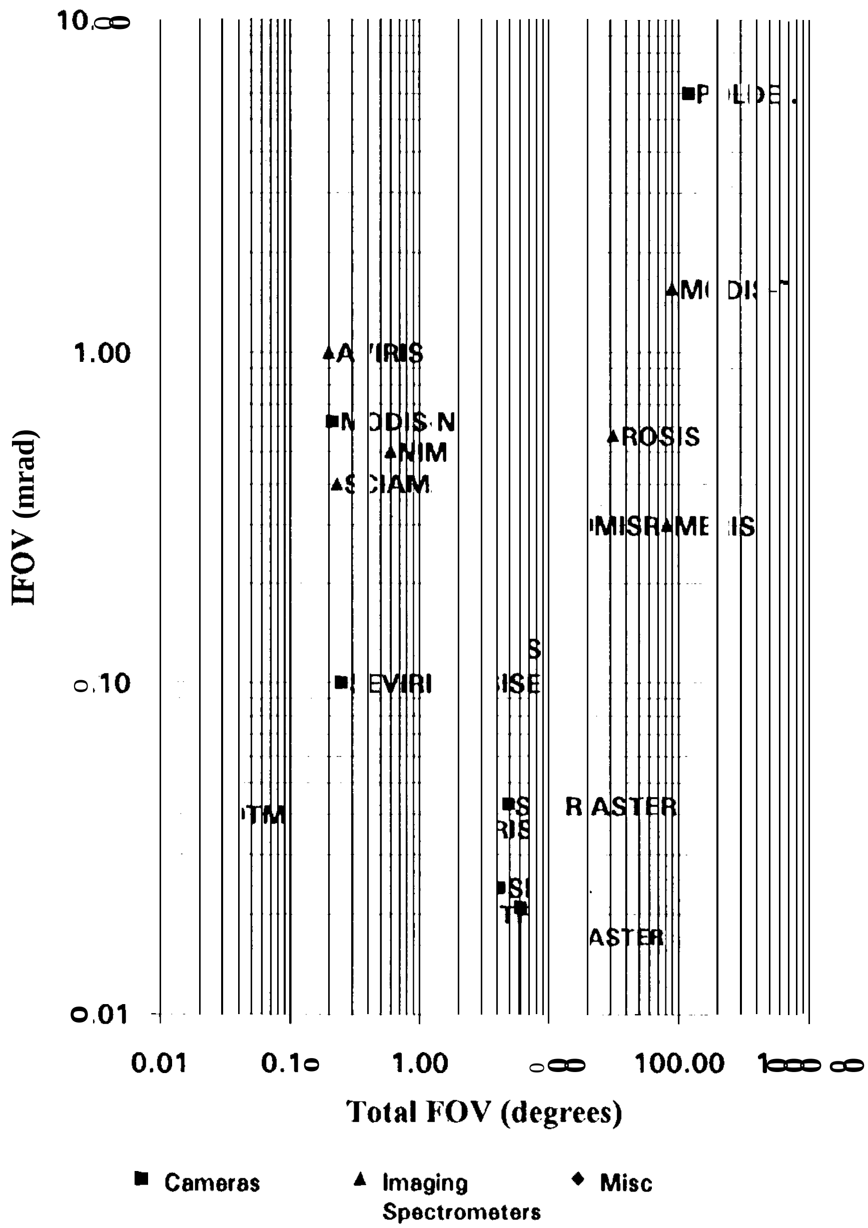


Figure 2. Spatial Performance



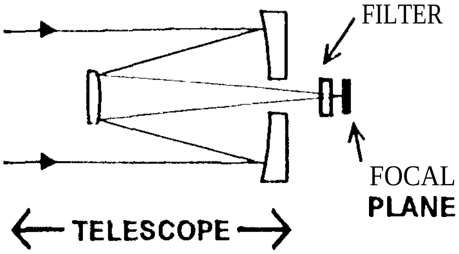


Figure 3, Multispectral Camera Schematic

The optical designs that arc used for multispectral cameras are loosely classified in table 2. For the visible region, lens systems arc used when the aperture is not excessive. For the infrared, the larger collecting apertures required favor reflecting systems, which also reduce problems with chromatic aberration. There arc exceptions, such as SWIR system for ASTER which uscs a 20 cm diameter lens in the infrared, The designers of this system claim that it has a weight advantage over an equivalent reflecting system. For large field angles and large collecting apertures, catadioptric designs tend to be used, as in SPOT4.

The development of wide-angle pushbroom cameras in the infrared is driven by the optical design performance. The ideal solution is to usc small detector pixels with a fast f-number system to maintain the light throughput. Unfortunately, fast f-numbers and large field angles are extremely awkward to implement with mirror systems. In fact, detector arrays can already be produced with more pixels than remote sensing optical systems can make usc of.

	TELESCOPE	FOCAL PLANE
MISR	Lens System	Field Filters
SPOT 4	Folded Catadioptric Telescope	Dichroic
SEVIRI	Ritchey Chretien	Field Filters
POLDER	Wide Angle Lens	Filter Wheel
VNIR/ASTER	Off-Axis Catadioptric/Aspheric Corrector	Dichroic
SWIR/ASTER	Lens System (20cm Aperture)	Field Filters
TIR/ASTER	Ritchey Chretien On-Axis	Field Filters
TM	Ritchey Chretien	Field Filters
MODIS-N	OfT-Axis Gregorian	Dichroics Field Filters

Table 2. Multispectral Camera Designs

2,3. Imaging Spectrometers

The schematic design of an imaging spectrometer is shown in figure 4, The telescope system focuses the light onto the entrance slit of the spectrometer. The spectrometer portion then disperses the image from each point on the slit onto a two dimensional detector array. On the detector array, the spatial dimension is in one dimension and the other dimension provides the spectral information. The motion of the spacecraft provides the pushbroom motion for the system.

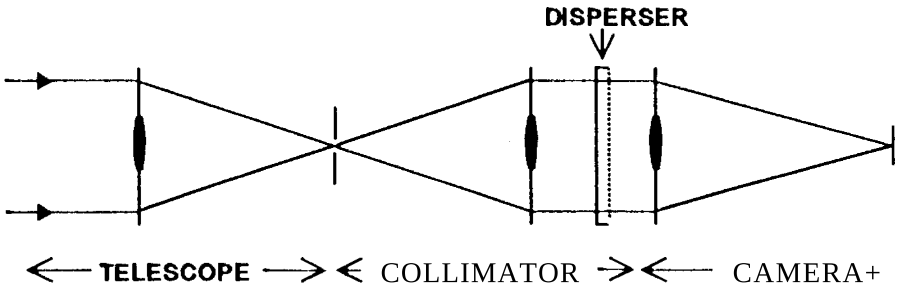


Figure 4. Imaging Spectrometer Schematic

The optical designs arc loosely classified in table 3. The requirements for the angular spatial field of view and the spectral resolution tend to determine the design choice.

For increasing angular fields of view the telescope designs progress from simple paraboloids, to Ritchey Chreticns, to Schmidt type systems and catadioptric designs. Refractive designs arc not used for two principal reasons, The first is because the narrow spectral bandwidths usually require a large collecting aperture to give an adequate signal to noise ratio. The second is to avoid problems with chromatic aberration duc to the large spectral ranges,

	TELESCOPE	COLLIMATOR	DISPERSER	CAMERA
MODIS-T	Off-Axis Paraboloid	Off-Axis Paraboloid	Schmidt Grating	Spherical Mirror
MERIS	Off-Axis Catadioptric	Refractive Corrector	Concave Grating	Refractive Corrector
SCIAMACHY	Off-Axis Paraboloid	Off-Axis Paraboloid	Plane Grating	Lens System
ROSIS	Off-Axis Schwarzschild	Off-Axis Schwarzschild	Plane Grating	Off-Axis Schwarschild
AVIRIS	Paraboloid	Off-Axis Spherical Mirror	Schmidt Grating	Off-Axis Mirror
NIMS	Ritchey Chretien	Dan Kirkham	Plane Grating	Ritchey Chretien
VIMS	Ritchey Chretien	Dan Kirkham	Plane Grating	Ritchey Chretien
SISEX	Reflective Off-Axis Schmidt	Off-Axis Schmidt	Prism	Off-Axis Schmidt
HIRIS	Reflective Off-Axis Schmidt	Off-Axis Schmidt	Prism	Off-Axis Schmidt

Table 3. Imaging Spectrometer Designs

Most imaging spectrometer systems usc gratings for dispersion because of their higher angular dispersion. The spectrometer camera focal length being too short to provide sufficient linear dispersion on the detector with a prism. The HIRIS and SISEX designs arc exceptions to this rule and usc multielement prisms to provide linear angular dispersions, but these designs arc extremely large on the order of 1000kg.

The spectrometer portion for an imaging spectrometer provides and interesting design challenge. Its size is solely determined by the aberrations in the design. Basically, shrinking the spectrometer in size, while maintaining the area solid angle throughput, cause its aberrations to increase as the angles through it increase. Better spectrometer design enable smaller spectrometers to be used in imaging spectrometers.

For wide angle systems Schmidt type systems have been used. Two of the instrument designs reviewed have novel design solutions. The first is MERIS which uscs an concave grating with a refractive corrector. The second is the design for ROSIS, which is based on an off-axis Schwarzschild type system. Although at first glance the mirrors in this system arc quite large compared with the f-number and detector size in the spectrometer.

There will undoubtedly be more solutions for this problem. Variable groove space gratings and binary optical gratings provide interesting possibilities in the future. Most of the classical spectrometer design have been derived solely on the basis of obtaining good spectral resolution. More work needs to be done in the future to produce good designs which take the spatial imaging aspect into account.

30 TECHNOLOGY UTILIZATION

The optical systems used in remote sensing instrument have benefited most from improvements in optical surface fabrication. Aspheric surfaces are now commonly used because diamond turning has made their fabrication much easier. If necessary, then post-polishing can be used to reduce the surface roughness. The VNIR/ASTER system will utilize an aspheric lens, and MODIS-T and AVIRIS both utilize gratings ruled on aspheric Schmidt correctors.

Blazed holographic gratings are now produced with low scattered light, and arc used in MODIS-T. None of the designs reviewed usc aberration corrected holographic gratings, because their peak diffraction efficiency is only 33%. This compares with a peak blaze efficiency over 90°A for a conventionally ruled grating. Increasing the entrance pupil diameter to overcome this loss in efficiency is usually to large a system impact.

Variable line spaced blazed gratings have been produced using numerically controlled ruling engines[24], and it is surprising that they are not utilized in any of the imaging spectrometer designs. They offer the possibility of reducing the size of the spectrometer system while maintaining a good diffraction efficiency. Binary optical gratings are likely to have an impact on spectrometer designs, and concepts based on their use arc discussed in the next section.

In multispectral camera designs filter efficiencies are extremely important. The new optical coating techniques have helped this, and SPOT4 has an efficiency of 98°/0 for its dichroic filters. Wide wavelength range high performance antireflection coatings will also improve the performance for multispectral camera optical systems.

Future multispectral camera designs are likely to incorporate active filter elements based on AOTF (acousto-optic tunable filters). An even more promising technology are liquid crystal based Lyot or SoIc type filters. In comparison to AOTF based systems these have the advantage of low power consumption and possibility of larger throughput apertures, which is always of prime concern for a remote sensing instrument.

4. FUTURE CONCEPTS FOR IMAGING SPECTROMETERS

Future spaceborne systems will require lightweight imaging spectrometers. The next generation of miniature spacecraft will only have 6 kilograms available for the instrument payload. In the past the planetary remote sensing imaging spectrometers such as NIMS weighed 20kg.

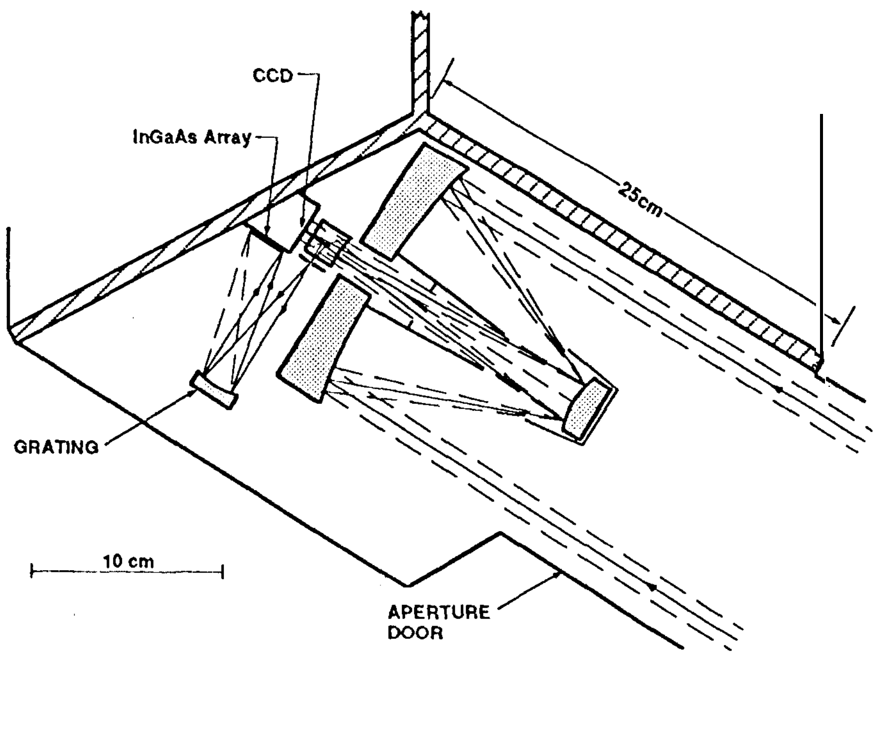


Figure 5. Microspacecraft Camera and Imaging Spectrometer

On microspacecraft for planetary remote sensing, future imaging spectrometers will be combined with the camera system to avoid the weight of an additional telescope system. Shown in figure 5 is one concept for an imaging spectrometer combined with a camera system. In this system a dichroic beamsplitter, separates out the light for the imaging spectrometer system. The single element spectrometer system is based on a variable groove spaced blazed grating which disperses and focuses the light onto an Iridium Gallium Arsenide detector array.

Binary optical gratings are also undergoing rapid development, and offer the possibility of producing a grating with complete control over the blaze and the groove positions. Thus overcoming the diffraction efficiency problems associated with aberration corrected holographic gratings, and without the restriction on holographic construction geometry. Their principal problem at the moment is stray light, but lithography techniques are making rapid advances.

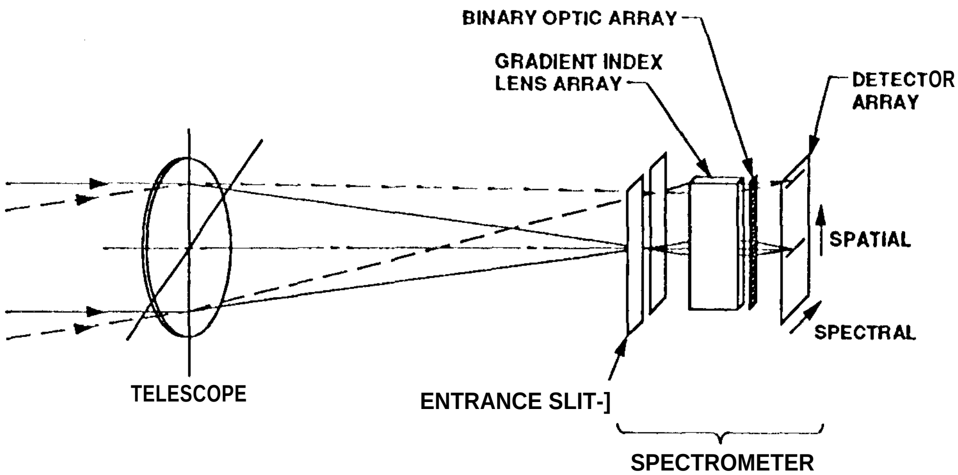


Figure 6. Imaging Spectrometer based on Binary Optical Grating Array

The use of binary optical gratings provides the possibility of new designs for imaging spectrometers. Shown in figure 6 is a design for a wide field of view imaging spectrometer based on an array of binary optical gratings. The use of an array of gratings reduces the angles through each individual grating, so enabling a reduction in size of the imaging spectrometer. With a conventional imaging spectrometer all the field angles must pass through the grating leading to severe aberration problems.

5. CONCLUSION

The optical design of imaging spectrometers is in its infancy. Unfortunately the very smallness of the field has limited its development. Hitachi has been using a numerically controlled ruling engine to produce variable line spaced gratings for the last decade[24], and yet there is still no facility with this capability in the United States.

Designing an imaging spectrometer with the current optical design programs is difficult. They arc extremely weak at optimizing the off-axis spectrometer designs used nowadays. Any real design work usually requires constraints that are so awkward to implement that the optimization dots not work properly. Unfortunately there arc fcw users of the modules of the program associated with diffraction gratings, so there is no pressure on program vendors to improve them,

In the past, the performance of imaging spectrometers and multispectral cameras have been limited by the available detector array sizes. The advance in detector technology has led to detector array sizes which exceed the current optical designs., The performance is now limited by the optical design.

Future remote sensing instruments will be smaller and have more capabilities, The challenge of providing useful instruments for microspacecraft, where the instrument payload is on the order of 5 kg, will Icad to ncw designs. The first approach to this problem will be the sharing of the optical telescope system by the camera and imaging spectrometer. The optical systems will also be rnadc lighter by utilizing the ncw material technologies such as silicon carbide and metal matrix composites will help with these systems. Finally, optics technologies such as binary optical gratings, and gradient index optics will lead to ncw more compact designs.

6. ACKNOWLEDGEMENT

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